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The Status of R&D for the Relativistic Heavy Ion Collider at Brookhaven

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THE STATUS OF R&D FOR THE RELATIVISTIC HEAVY ION COLLIDER AT BROOKHAVEN*

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Abstract: Formal development of the Relativistic Heavy Ion Collider (RHIC) has been funded for the past three years. Prototype superconducting magnets and cryostats have been tested. Detailed designs have been prepared for the arc sections, the insertion regions and injection and ejection systems. The RF system has undergone significant revisions in order to enhance the experimental capability of RHIC. Progress has been made with the design of detectors. We are putting in place a management information system in anticipation of an expeditious start of construction.

Introduction

There can be very few accelerators built in the past which were subject to the initial constraints put upon RHIC. These constraints include an existing tunnel, experimental areas and cooling plant and a well defined range of particles available for injection. Nevertheless, an attractive design has been produced for a collider which promises a unique experimental physics program which will be unmatched well into the next century. When completed the RHIC complex employ many of the accelerators on site in order to pre-accelerate particles prior to injection into RHIC. The completion of the heavy ion transfer line was an important step in the sequence and permitted to start of a heavy ion physics program at BNL with the availability of ions up to mass silicon.[1] The completion of the AGS Booster accelerator in 1991 will extend the range of particles for acceleration in the AGS up to gold.[2] In addition the proton intensity will be increased by a factor of four to five. If the present worth of all the facilities on hand (including the Booster) are summed then RHIC may be considered as a relatively small increment on the existing investment of about half a billion dollars. The formal R&D program started in fiscal year 1987 and has two major components; R&D on the accelerator system which is now in full stride and R&D on detectors, which will formally start in fiscal year 1990. The expenditures on the various subsystems of RHIC during the R&D phase are shown in Table 1, this table is taken from the recently published R&D plan for RHIC.[3] The early emphasis on arc magnet R&D is intended to mesh with a proposed construction start in the near future. Such a strategy enables industrial fabrication of arc magnets to gear up while R&D on the remaining subsystems proceeds. The total expenditures on accelerator systems R&D totals some $24 million. Over the period prior to accelerator start-up the R&D on detectors amounts to about $9 million.

Prior to fiscal year 1987 a small R&D effort devoted to the fundamental issues of designing a heavy ion collider and conceiving of an experimental physics program was supported by funds from the Director's discretionary exploratory research program. The small expenditure was extremely effective in getting RHIC started. Four full-length dipole magnets were made, of which three were assembled by commercial firms.[4] The basic structure of the lattice was chosen and a Task Force was appointed to coordinate the activities of potential users and to develope a realistic experimental program.

The R&D Program

RHIC consists of two main rings, separated radially by 90 cm, center to center, except where they cross at six points. Each ring has six cryogenic arcs containing twelve cells, the phase advance per cell is 90°. The twelve cells form a continuous cryogenic enclosure which is terminated at either end by the transition to a room temperature straight section which can contain injection, ejection, RF cavities and the magnets necessary to achieve the focussing and bending at the insertions. The two rings are filled by means of transfer lines from the AGS. Two RF systems are proposed: one to capture and accelerate the beam, the second system is designed to minimize growth in the diamond at the beam intersection regions during storage. Methods of injecting and ejecting the beam have been considered in some detail. Descriptions of the machine have been published[5], in addition a revised Conceptual Design Report has just been issued.[6] The performance goals of RHIC are shown in Table 2.

Machine R&D

A final design for the lattice was frozen in 1988. It was designed to ensure an adequate physical aperture for the beams for specified values of beam emittance and momentum spread. The lattice has demonstrated tuneability over a range of $\Delta\nu = + 1$ and provides for β^* of 2 to 6 m for each insertion. All insertions can be tuned independently. A set of sextupoles divided into six families is provided to control chromaticity and to minimize the dependence of betatron tune and other lattice functions on off-momentum error.[7] The dependence of tune on betatron amplitude has been investigated, the proposed sextupole arrangement also minimizes this aberration effect. Many questions concerning the dynamical aperture have been resolved by means of computer tracking programs, this work included a comparison of several accelerator codes.[8] The lattice design allows storage and collision with both similar and dissimilar particles in each ring.

The question of transition energy crossing has been investigated in detail and methods proposed to minimize beam blow-up.[9,10] A set of pulsed quadrupoles have been included in the lattice which permit a rapid change in transition energy as the beam approaches this point.

About a year ago a workshop was held at Brookhaven[11] to evaluate the performance anticipated in light of experience of other colliders such as the Tevatron and SPS. As a result of the workshop a major

Table 1

RHIC R&D Summary Estimates
$ in Thousands

		Prior Years	FY89	FY90	FY91	FY92	FY93	FY94	FY95	Total
WBS 2.1.1	Magnet System	4558	2558	2560	1195	129	0	0	0	11000
2.1.2	Mag. Elec. Sys.	25	33	74	100	167	149	90	50	688
2.1.3	Cryogenic System	248	299	300	625	560	450	275	0	2757
2.1.4	Vacuum System	50	50	110	150	135	90	90	35	710
2.1.5	Injection System	50	70	95	180	160	115	100	35	805
2.1.6	Beam Dump System	50	70	115	250	220	145	145	35	1030
2.1.7	RF System	50	80	180	313	285	165	100	35	1208
2.1.8	Beam Instrum.	50	100	90	80	80	60	40	35	535
2.1.9	Control System	25	50	55	70	320	340	180	107	1147
2.1.10	Acc. Physics	288	444	183	183	183	123	123	55	1582
2.1.11	Administration	770	535	155	155	155	155	155	80	2160
WBS 2.1	Accelerator Systems	6164	4289	3917	3301	2394	1792	1298	467	23622
WBS 2.2	Detectors	0	0	651	931	1770	2235	1842	1240	8669
	Subtotal	6164	4289	4568	4232	4164	4027	3140	1707	32291
	G&A	2636	1911	1732	1968	1936	1873	1460	793	14309
	Total 89 $	8800	6200	6300	6200	6100	5900	4600	2500	46600

Table 2

General Parameters and Design Goals for RHIC

Energy Range (each beam), Au	7-100 GeV/nucleon
protons	28.5-250 GeV
Luminosity, Au beams	
@ γ = 100 and 22 cm rms diamond	2×10^{26} cm^{-2} sec^{-1}
Maximum diamond length	$\pm$ 22 cm rms
Operational lifetime Au @ $\gamma > 30$	$\gtrsim$ 10 h
Circumference, 4 3/4 C_{ags}	3833.85 m
Number of X-ing points	6
Free space at X-ing point	$\pm$ 9 m
Beta @ X-ing, horizontal/vertical	6 m
low-beta insertion	2 m
Betatron tune, horizontal/vertical	28.82
Transition Energy, γ_T	24.7
Filling mode	Box-Car
No. of bunches/ring	57
No. of Au-ions/bunch	1×10^9
Filling time	$\sim$ 1 min
No. of dipoles (180/ring+12 common)	372
No. of quadrupoles (276 arc + 216 insertion)	492
Dipole field @ 100 GeV/nucleon, Au	3.45 T
Dipole magnetic length	9.46 m
Dipole yoke length	9.7 m
Coil i.d. arc magnets	8 cm
Beam separation in arcs	90 cm
rf voltage (26.7 MHz-acceleration)	0.4 MV
rf voltage (160 MHz-storage)	4.5 MV
Acceleration time	1 min

change to the design of the RF system was made. The intent of the change is to eliminate the need for beams to cross at a shallow angle and instead to meet head-on. This will eliminate a non-linear betatron - synchrotron coupling observed at the SPS. In order to maintain a small diamond over which the beams interact of $\pm$ 22 cm (rms) over the beam life time a separate high frequency RF system was proposed. This change necessitated further studies of beam-beam effects.[12]

Injection and beam abort (ejection) studies have covered two major topics:

1) The complete injection sequence all the way from the source. Electron stripping strategies to achieve the maximum particle intensities have been examined.[13]

2) Injection and ejection trajectories and design of magnets, inflectors and kickers to achieve them. An internal beam dump will be used initially.

The next milestone to be achieved in the R&D Plan is the finalization of the correction scheme and a strategy for shuffling the arc dipoles.[14] The correctors systems in both the arc and insertion regions will correct for magnet imperfections, skew coupling and trim errors so that a closed orbit can be achieved.[15]

Hardware Development

Turning to hardware development, emphasis has been given to the early perfection of magnet designs for the cryogenic arc sections. The magnet is defined to consist of the cold mass and its cryostat. In addition to the dipole magnet R&D, there has been substantial progress in the development of quadrupoles, sextupoles and correctors for the arcs; the development of quadrupoles is largely completed and initial sextupole and corrector magnets are being built and are approaching the testing of their design. The dipole design incorporates several features which set it apart from that of other superconducting accelerator magnets, e.g., those for the Tevatron, HERA, or the SSC. It has a relatively large bore (80 mm) to accommodate the emittance growth associated with intrabeam scattering, a modest operating field (3.45 T), a single layer cosine theta coil, an iron yoke assembled as collars, a copper-plated bore tube and no internal trim coils. The effective magnetic length is 9.46 m. Other parameters are listed in Table 3.

To minimize cost and to take advantage of ongoing development, the magnet uses superconducting cable of the same type as the cable developed for the outer coil layer in the dipoles for the SSC. This is a flat, keystoned 30-strand cable of the Rutherford type. The (bare) cable width is 9.73 mm and its aver-

Table 3

Dipole Parameters

B_o, injection	0.40 T
B_o. 100 GeV/nucleon	3.45 T
Current, 100 GeV/nucleon	4.98 kA
Inductance	29 mH
Stored energy @ 3.45 T	397 kJ
Length, effective	9.46 m
Length, mechanical	9.81 m
Sagitta, mechanical	49.3 mm
Coil, number of turns	32
Coil, inner radius	39.9 mm
Iron, outer radius	133.3 mm

age thickness is 1.17 mm, with a keystone angle of 1.2 degrees. Each wire is 0.65 mm in diameter, containing high-homogeneity NbTi filaments 6 μm in diameter. For the initial R&D magnets the copper-to-superconductor ratio was 1.8:1 and the critical current density of the wire (@ 5 T,4.2 K) was 2200-2600 A/mm^2. To give added stability against quenching and to allow for single-diode quench protection with a suitable margin of safety, the revised specification for the copper-to-superconductor ratio is 2.25:1. The current density is now specified at 2600 A/mm^2, taking advantage of improvements made in superconductor technology in the last few years.

Prestress is applied to the coil directly by the iron yoke through a 10 mm thick combination of glass-phenolic insulator and brass spacer package keyed into the yoke lamination, i.e., not by a non-magnetic collar as used in the dipole for the SSC. A stainless steel shell which is split and welded at the vertical mid-plane takes over the compression of the yoke when it is at cryogenic temperature. The iron saturation at the highest operating field is corrected with lumped correctors outside the dipoles. A recent small adjustment of the design spaces the coil a total of 10 mm from the iron to reduce the saturation effects. The magnets are assembled in fixtures that introduce the required curvature; this curvature is locked in place via the outer stainless steel weldment referred to above which also serves as the helium pressure vessel.

The RHIC dipole R&D program has included several types of model magnets. The first models utilized, for expediency, coils wound at Fermilab to the pattern of inner Tevatron coils using CBA/Tevatron cable, but 4.5 m long. One of these coils was inserted into a CBA iron yoke that had been adapted to the correct coil diameter by means of laminated iron spacers. Four other 4.5 m long coils were collared at DESY, inserted into bent HERA yokes at Brown, Boveri & Cie. (BBC), Mannheium, Federal Republic of Germany, and returned to BNL for testing. Two were assembled with aluminum collars between coil and yoke, and two with iron collars. All of the magnets met their expected conductor short sample performance with little training. Next came a single 4.5 m long magnet which served as a shorter prototype for full length magnets. This magnet also reached a quench plateau in good agreement with short sample predictions, and its harmonics were well with the expected error distribution.[16]

The first full-length R&D magnets consisted of four dipoles[4] designated DRA-001 through DRA-004. The cold mass of the first of these tested, DRA-004, was constructed entirely at BNL (utilizing a keyed yoke) and installed in a horizontal HERA cryostat supplied by BBC. Coils for the remaining three were also produced at BNL. They were subsequently sent to BBC for cold mass assembly (with welded yokes) and insertion into cryostats, and were returned to BNL for testing. The

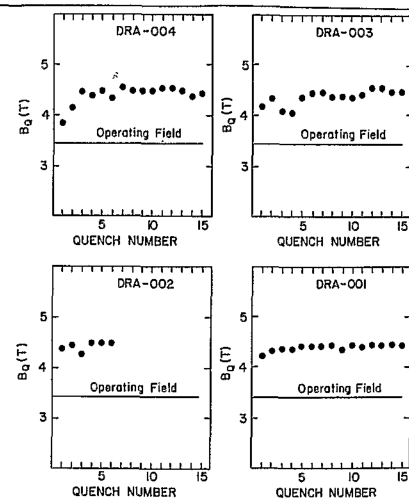

Fig. 1. Training History of Dipoles DRA-001 - 004.

quench data for these dipoles are shown in Fig. 1. As can be seen, the quench fields were all well above the operating field and training was minimal. The measured allowed harmonics for DRA-004 generally agreed with calculations within the estimated magnet-to-magnet variation expected from construction tolerances; these harmonics in the other three magnets exhibited an offset that was not complete BNL and BBC of the size of the shim near the pole. The unallowed harmonics measured in all the magnets differed from zero by less than the amount expected from construction errors. The saturation characteristics of the BNL-built magnet DRA-004, differed from those of the BBC-built magnets; this difference was ascribed to the differences in iron used at BNL vs. that used at BBC. The field normal to the magnetic median plan in the magnets varied somewhat greater than would be desirable for machine magnets. The measurement probe used for measuring the fields in these magnets was one developed for use in 17 m SSC magnets.

In summary, these magnets were considered quite successful and were productive in illuminating areas in which difficulties can arise in the commercial fabrication of accelerator magnets.

The most recent R&D magnets, DRB-005 and DRB-006, have just completed the testing stage. These magnets have a coil design modified from the earlier verison to reflect the thicker cable being used, an increased gap (total 10 mm) between the coil o.d. and the iron i.d., and the post-type cryostat intended for use in the machine. The quench results for these two magnets are shown in Fig. 2. Both performed well above the required field value from the first quench. The magnetic field measurements were within the bounds expected from construction tolerances although some adjustment of the systematic, allowed multipoles will be required. Experience gained in the assembly and testing of these magnets will lead to minor modifications in the construction of the final two BNL R&D arc dipole magnets, DRC-007 and DRC-008. R&D issues remaining in the dipole program include the actual measurement of various parameters such as multipoles above the decapole, the alignment of the dipole median plane, and ramprate-dependent effects.

Two arc quadrupole magnets, QRA-001 and QRA-002, have been built and tested. Their quench performance was well above the required level. The field quality measurements indicated multipole structure well within the allowable tolerances. Sextupole and corrector magnets are currently under construction and testing of the first models indicates good performance.

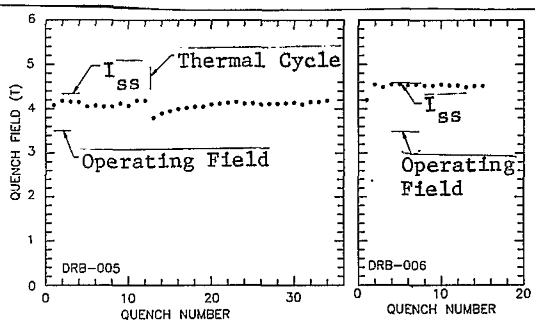

Fig. 2. Training History of Dipole Magnets DRB-005 and DRB-006.

Ongoing magnet R&D is devoted to the construction of a Full Cell Test. The cell consists of two half-cells each containing a dipole, quadrupole, sextupole and corrector magnets. This will require the design of magnet interconnections, bellows and pick-up electrodes.[17] In addition, the preparation of specifications, drawings and process procedures for use in the industrial manufacture of magnets will proceed, leading to a contract for industrial tooling and the industrial assembly of two dipole cold masses using coils supplied by BNL and tooling which is available to industry as part of an arrangement with DESY. The purpose of this contract is to learn as quickly as possible if there are any remaining problems in the industrial fabrication of machine-ready cold masses. The involvement of potential industrial sources for the magnets is a major addition to the R&D program. This work was added after funding for construction did not materialize in FY 1989 and to some extent it should reduce the time for industrial magnet vendors to gear up for production once construction is funded.

The cryostat housing the cold mass consists of the carbon steel vacuum vessel (610 mm outer diameter), an aluminum heat shield maintained at 55 K, blankets of multilayer fabric and aluminized Mylar, cryogenic headers, and the magnet support system. The design calls for dipole cold mass to be supported at three locations by means of the folded, insulated post-type support developed originally at Fermilab for the SSC magnets and adapted at BNL for use in RHIC. A standard arc dipole will have three such supports and the standard arc quadrupole will have two. The vacuum tank are carbon steel castings. The surface of these legs are used to provide the exterior survey fiducial references used to survey and align the magnets into their position in the tunnel.

Allowance will be made for relative thermal motion of the cold mass, piping, heat shield and vacuum tank with respect to each other by means of expansion joints (bellows) located in the interconnect region between magnets. This region has been designed to facilitate connections between magnets after they have been installed in the tunnel and to permit ready removal of a magnet if that should ever become necessary. Careful design is required to fit all necessary hardware into this region, hold the heat leak to the desired low value, and achieve an economically acceptable solution.

Major components of the cryostats for magnets DRB-005 and DRB-006 were fabricated by commercial sources. A second generation design cryostat will be used for DRC-007 and DRC-008. The components for these cryostats as well as those for QRA-001 and QRA-002 will be fabricated commercially and assembled at BNL. As these cryostats are assembled for use in the Full Cell mentioned above, they will be evaluated for ease and economy of assembly and disassembly, compliance with heat leak allowances for them and positional (survey) accuracy. If necessary, the design will be modified on the basis of this evaluation to prepare for industrial production.

Other R&D Issues

During the R&D phase of a project a good many problems must be dealt with beyond the rather obvious need to refine the design. Nowadays safety and environmental issues of the completed machine must be addressed early on before construction begins. A great deal of pre-construction planning is required to prepare budgets, schedules and cost estimates. The creation of a versatile Work Breakdown Structure (WBS) is an essential tool in the computerized versions necessary for a large project. The WBS must assist all levels from managers to working engineers. Typical requirements include:

- Management summaries at the cost account level, as well as a structure depicting geographic location of the machine components.
- Integrated Date Base collecting cost and manpower at the lowest WBS level.
- Data which is timephased to year of obligation, thus permitted changes in the yearly funding profile to be accommodated.
- Milestone schedule and procurement plans based on the current profile.
- Current Working Estimate (CWE) of cost based on latest material and labor projections.

Another issue of some importance is the improvement capability inherent in the machine design which can be exploited after initial construction is finished. The improvements should be made by means of relatively modest technical changes which will not require significant revisions of the magnets in the cryogenic arcs. Thus RHIC as constructed should not preclude later upward revisions of the performance if desired but it should initially be built within the constraints of the validated cost and schedule.

An increase of particle intensity should be possible beyond the values shown in Table 2 by means of higher injected beam currents and filling empty RF buckets. At some stage of improvement an external beam dump may be required. The use of very low beta insertions with the increased beam intensity should provide ultimate luminosities for the proton beams of about 2×10^{32} cm^{-2} sec^{-1}. Average luminosity may be improved by stochastic cooling schemes. Assuming the components in the cryogenic arcs remain unchanged for the lifetime of RHIC, increases in energy could come from the addition of power supplies. The maximum energy will be limited by magnet performance and will be about 120 GeV/amu for gold on gold (300 GeV for proton on proton). These energies correspond to similar species in each ring and may not be achievable simultaneously with the maximum ultimate intensity as the available margin of cooling will be reduced by both high energy and high intensity.

Detector R&D

The detectors which will be built for research at the heavy ion collider will have much in common with large detector systems at other high energy colliders. There are, however, some important, and dramatic new features of the experimental environment at RHIC which will require the extension of known techniques for particle detection beyond the present ranges of application in elementary particle and nuclear physics. Central to the research goals at RHIC is the need to produce, detect and study collisions of unprecedented complexibility: it is to be a laboratory for the study "mini-big bang" events. With beam energies up to 100 + 100 GeV/nucleon and ion masses over 200, the total energy in each collision can reach up to 40 TeV in the center-of-mass: a range far beyond that of any present accelerator or any existing detector system. Unlike the proposed SSC collider, which would accelerate elementary particles to such an energy and produce hundreds of very high energy particles in the final state, the most interesting events at the RHIC collider are expected to produce tens of thousands of final-state particles in each collision, with proportionately less energy carried away by each particle. Thus, while the basic detector technology will have much in common with the detector systems developed for colliding beams of elementary particles, the design of detector systems for the heavy ion collider must address a different set of problems. Detector systems to deal with high energy nucleus-nucleus collisions will require new approaches to the technologies of tracking, calorimetry, particle identification, fast trigger decisions and on-line data processing.

It is expected that the RHIC facility will begin operation with 3 or 4 major detector systems. The machine is configured to ultimately allow for 6 instrumental collision regions. The research program is expected to involve 300 - 500 physicists, with the design and construction of detectors spanning a period of about five years.

Beginning in April 1985, a series of workshops[18,19,20] has been held in which physicists from many laboratories and universities have carried out a detailed examination of possible experiments for RHIC. Several well-developed designs for experiments have come out of these workshops, and these have served as a basis for cost estimates and for pin-pointing R&D requirements. The following areas have been identified as most urgently requiring study before the design of large-scale detector systems can be completed:

- Tracking detectors for very high particle density.
- Calorimeter response to nuclear interactions.
- Methods of muon and electron pair detection suitable for studies at transverse momenta and pair masses = 1 GeV.
- Radiation hardness of detectors and circuit components.
- Design and instrumentation of test beam facilities.
- Development of Monte Carlo event generators.

At the May 1987 workshop a few of the designs for large detector systems were examined in detail to study their technical feasibility, their impact on the design and modes of operation of the collider and the range of capabilities for physics research represented by each. Out of these studies came the realization that the measurement of lepton pairs, (electron pairs and muon pairs) radiating from heavy ion collisions and RHIC cannot be adequately measured if the luminous interaction length of the crossing beams is of the order of a meter or more, as it was in the original RHIC design. Since these lepton pair measurements are of fundamental importance to the research program at RHIC, the design of the RF system of the machine was revised to provide shorter beam bunches as described above. These workshop studies are also showed that the most useful improvements to the machine performance - from the point of view of extending the physics reach - would be those which increased the luminosity of the machine, rather that extending the energy range.

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